

Wave Climate and Wave Mixing in the Marginal Ice Zones of Arctic Seas, Observations and Modelling

Alexander V. Babanin
Swinburne University of Technology
PO Box 218 (H38)
Hawthorn, Victoria 3122 Australia
phone: +61-3-9214-8033 fax: +61-3-9214-8264 email: ababanin@swin.edu.au

Ian R. Young
The Australian National University
Canberra, ACT 2000 Australia
phone: +61-2-6125-2510 fax: +61-2-6257-3292 email: ir.young@anu.edu.au

S. Zieger
Swinburne University of Technology
PO Box 218 (H38)
Hawthorn, VIC, 3122, Australia
phone: +61-3-9214-5430 fax: +61-3-9214-8264 email: szieger@swin.edu.au

Grant Number: N00014-13-1-0278
<http://ababanin.com/>

LONG-TERM GOALS

The long-term goals of the present project are two: wind/wave climatology for the Arctic Seas, and their current and potential future trends; and WAVEWATCH-III® and SWAN wave models with new physics, adapted and validated for the Beaufort and Chukchi Seas.

OBJECTIVES

The wind/wave climatology for the Arctic Seas will be developed based on altimeter observations. It will have a major scientific and applied significance as presently there is no reference climatology for this region of the ocean available. The new versions of wave models for the Beaufort and Chukchi Seas will include new physics that is already under development, and the novel physics presently unavailable. In particular, it is planned to use a wave boundary layer model to replace traditional wind-input parameterisations. The models will be suitable for operational forecast. Altimeter climatology and the wave models will be used to study the current and future wind/wave and ice trends.

APPROACH

Spaceborne radar altimeters have observed the oceans for more than two decades with an almost continuous record since 1985 (Fig. 1). Pulse-limited radar altimeters can estimate wave height and are also able to provide information on surface winds, ocean swells and on storm events, and on the respective trends in these quantities (Young et al., 2011, 2012, 2013). Satellites equipped with altimeters operate on various orbits, which determine the repeat cycle, inclination angle, altitude etc. With change in the inclination angle, global coverage and repeat cycle also change. An

inclination angle close to 90 degrees yields better data coverage in the polar regions such as Arctic. In this regard, coverage of instruments operated by NASA/CNES (i.e. JASON1/2, TOPEX) ends at approximately 67 degrees north/south. Altimeters of the European Space Agency, and recently the Chinese HY2 and Indian/CNES SARAL missions cover up to the 80th degree north/south and higher. Starting from ERS1 which was launched in 1991, these are polar areas up to 82 degrees North, with the latest CRYOSAT altimeter measuring waves and winds up to 88N (provided these waters are open). Therefore, information on wave climate is available over the entire period of existence of the marginal Arctic ice zones.

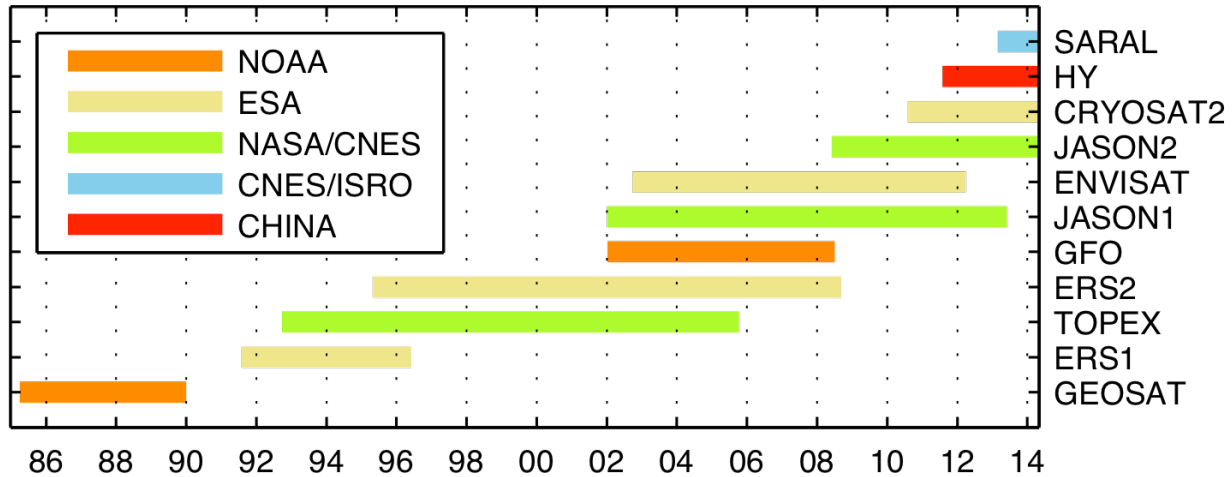


Figure 1. Altimeter missions by Agency (1985-2015).

The Swinburne altimeter database does contain information on the Arctic Seas (now including the HY and SARAL missions), but it was not utilised, since the authors were originally interested in annual trends, and these Seas were and still are covered with ice for most of the year. Altimeters record the signal returned from an illuminated surface, which can be over sea, land or ice. In transition from sea to land, the return signal shows distinct spikes, but this is not the case for sea/ice transition and therefore separating the ice from the ocean/sea is ambiguous.

Separation of measurements over sea ice from measurements over the open ocean was the initial task of this project. The selected algorithm should be versatile and applicable to various missions. It has been demonstrated that sea ice can be detected if brightness temperature data, available from radiometer instruments, is considered (Tran et al., 2009). Radiometers, however, are typically not available on many altimeter platforms. Therefore, as the first aim of the project, a more versatile approach (Laxon, 1990, Rinne and Skourup, 2012) was selected to be verified against the method proposed by Tran et al. (2009). At subsequent stages of the project, the same method is applied to altimeter data at latitudes greater than 67 degrees North (i.e. ERS2, CRYOSAT).

The second main goal of the project is to advance the physics of wave-forecast models in general, and with respect to the Arctic Seas in particular. Third-generation wave models are about 30 years old, but it is only now that their physics is going through significant updates (Ardhuin et al., 2010, Babanin et al., 2010, Tsagareli et al., 2010, Rogers et al., 2012, Zieger et al., 2015). Overall forecast of the waves with the present models is reasonable, except for non-standard situations, where the balance of the source terms is not satisfied or the parameterisations are not suitable due to some missing physics or due to limits of the range of their original applicability. Such situations are frequent and well known. Waves in marginal ice zones is certainly one of such situations.

One of the most essential new contributions to the physics of wave models planned for this project, is that for the wind-input term. Up to date, it seems to be the most developed source function, as it refers to analytical, laboratory and field observation in a greater regard than any other term employed in such models. On the close scrutiny, however, significant issues remain unanswered and even uncovered. While the models typically take U_{10} or other mean wind speed as an input property, from the atmospheric models or from observations, they ultimately use friction velocity u_* . To convert one into another, so called drag coefficient C_d is employed. This purely empirical property is meant to replace the entire physics of the boundary layer. As a result, it is not a single number and not even a simple function of the wind or wave age, as it is often presented, but depends on very many properties and features of the air flow, boundary layer, ocean surface, wave fields and wave dynamics (Babanin and Makin, 2008, Babanin, 2011, Ting et al., 2012, Toffoli et al., 2012). As a result, scatter for parameterisations of the sea drag is formidable and cannot be improved unless the variety of parameters is properly accounted for. It is quite likely that the Arctic environment, particularly the Marginal Ice Zones, will pose another set of parameters for such dependences. Combining all the wind, wave, ocean, ice, boundary-layer and other properties into an accurate parameterisation is not feasible and not practical.

Therefore, the next logical step in advancing the wave models would be to employ a model of wave boundary layer (WBL) instead of parameterisations of the wind input. Such model would take the mean wind speeds as an input and convert them into pressure working on the ocean surface, without relying on the sea drag or other substitutes for the physics of WBL. An approximation of the 1D version of the Chalikov and Rainchik (2011) WBL model is now available at Swinburne. The major step forward in wave modeling is in progress, by implementing a wind-input function based on this WBL in WAVEWATCH-III.

WORK COMPLETED

This is a report for the third year of the project. 2015 marks a number of common efforts within the Sea State DRI, including the main event of this DRI - the field experiment in the Beaufort Sea, and the community paper (Thomson et al., 2015). Fig. 2 (left) shows map of altimeter tracks predicted for the research cruise, Fig. 2 (right) ENVISAT observations of the relative changes of the multi-layer/first-year ice cover in the domain of Chukchi and Beaufort Seas, contributed to the joint paper by the Swinburne group.

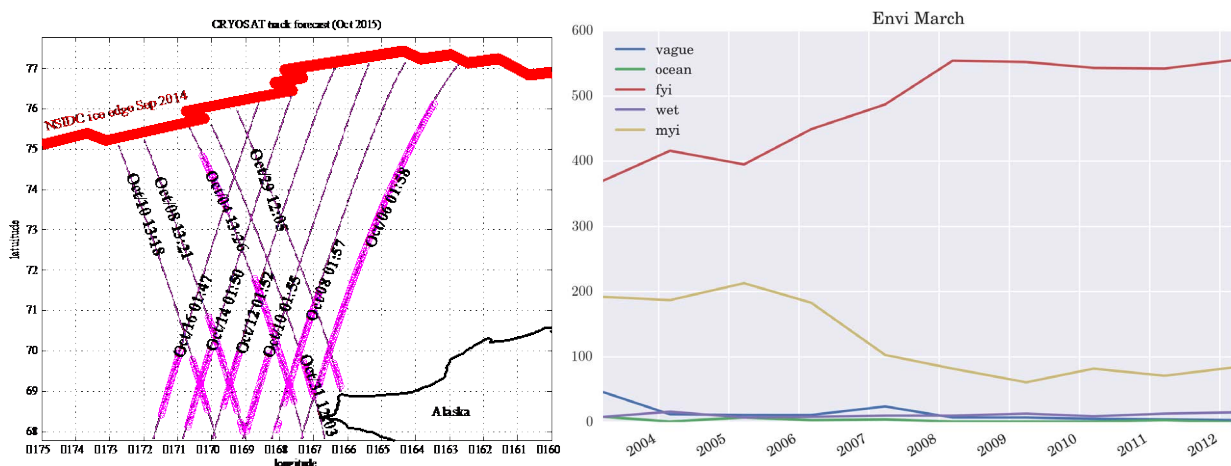


Figure 2. (from Thomson et al., 2015) (left) CRYOSAT tracks over the field experiment area for October 2015; (right) ENVISAT observations of the multi-layer (brown) and first-year (red) ice cover in the Chukchi and Beaufort Sea domain.

In the first year, the altimeter database which was available at Swinburne for the period 1985-2008, was extended to 2012, end of the mission for ENVISAT. The separation of altimeter measurements over ice from measurements over the open ocean was performed. This allowed us preliminary analysis of trends for wave heights over areas of the Arctic Ocean free of ice over the period of 2002-2012 (Babanin et al., 2014). WW3 subroutine for Wave Boundary Layer module was prepared and tested.

In the second year, the CRYOSAT (new satellite) data was quality controlled, and calibrated and validated against NDBC buoys over the period August 2010 to May 2014. In addition to the buoys, validation of this data was performed against calibrated JASON1 and JASON2 observations for four years (2010-2014). An approximation of the WBL model was implemented as a subroutine in WAVEWATCH-III. The skill of the WBL model in WAVEWATCH was validated by means of academic tests.

In the third year, satellite database continued to be extended both for CRYOSAT and to accommodate new altimeter missions (HY2 and SARAL) and to include also SSM/I, scatterometer and SAR data (see IMPACT Section). The remote-sensing part of the project was concentrated on reprocessing of ENVISAT (2002-2012) and CRYOSAT (2012-present) data, in order to optimise the grid size so that the trends are robust in time and smooth in space.

Within the wave modelling part, the new wind-input function developed for WAVEWATCH-III underwent further testing and calibration. Now, this was done by means of hindcasting real environmental conditions in Lake Michigan (no swell), and comparing them with observations.

Two papers were published in collaboration with the other DRI groups (See RELATED PROJECTS Section). With the group of Rogers, observation/modeling study of an energetic wave event in the Arctic marginal zone was conducted (Collins et al., 2015). Laboratory experiments on reflection and transmission of water waves by ice floes were performed with the group of Squire (Bennet et al., 2015).

These and other results are outlined in the following Section.

RESULTS

The 2002-2014 ENVISAT/CRIOSAT database have been used to obtain the wave climate in the Arctic and its trends. Trends are obtained for mean H_s and U_{10} , as well as for their 90th and 99th percentiles, over 75 and 150 km square grids, over the entire 2002-2014 periods and over sub-periods of 2002-2006 and 2007-2014 (presuming a change of ice regime occurred in the Arctic in 2006 – see Fig. 2 (right)). Work with ERS2 data has commenced in order to extend the time series into the period before the regime change.

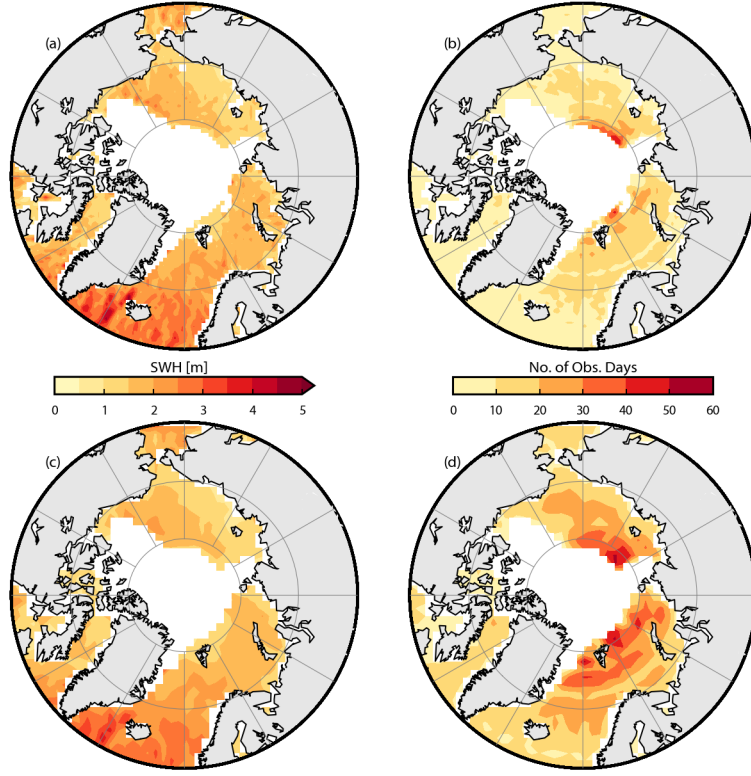


Figure 3. The mean wave height (a, c) and the sampling days (b, d) of ENVISAT altimeter through August to September 2007 for different cell size: 75 km (a, b) and 150 km (c, d).

Fig. 3 illustrates both the trends and the problem of grid size. 75 km grid was chosen originally as been large enough for estimations on the Chukchi-Beaufort domain scale of Thomson et al. (2015). At DRI meetings, it was criticised for giving filamental structure on the map of the trends (see e.g. Fig. 3a, particularly in the North Atlantic area). These filaments are caused by prevailing satellite tracks and low sampling rates when the grid size is small (Fig. 3b). Doubling the grid size to 150 km smoothed the trends (Fig. 3c) due to the increased sampling (Fig. 3d), and this is now the preferred grid.

Fig. 4 demonstrates results of WAVEWATCH-III model testing for Lake Michigan. For a selected point, the plots show source functions (nonlinear term, whitecapping dissipation and the new wind input), as well as their sum, and the wave spectrum. Left panel is 1-hour development, and the right panel after 12 hours.

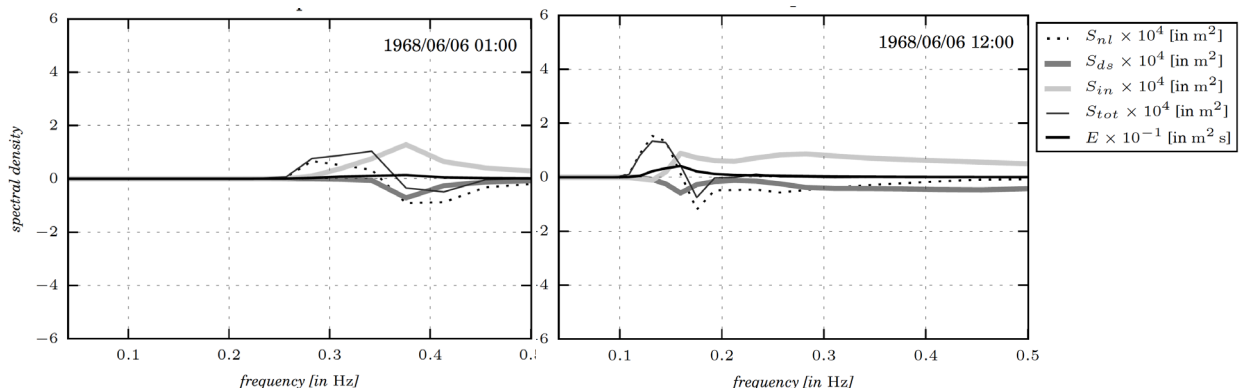


Figure 4. Lake Michigan test of WAVEWATCH-II with the new wind input term; spectra shown are as in the legend. (left) 1 hour development; (right) 12 hours.

In Fig. 5, application and development of spectral wave models, in particular wave-dissipation and wind-input terms suitable for various wave-ice conditions, is shown. This is validated by means of field observations of the largest wave event records in the Arctic ice-covered region so far. The event distinguished three different dynamics of wave-ice interactions: wave blocking by ice, strong attenuation of wave energy and fracturing of ice by wave forcing, and further uninhibited propagation of the peak waves (after leaving the ice pack) and an extension of allowed waves to higher frequencies.

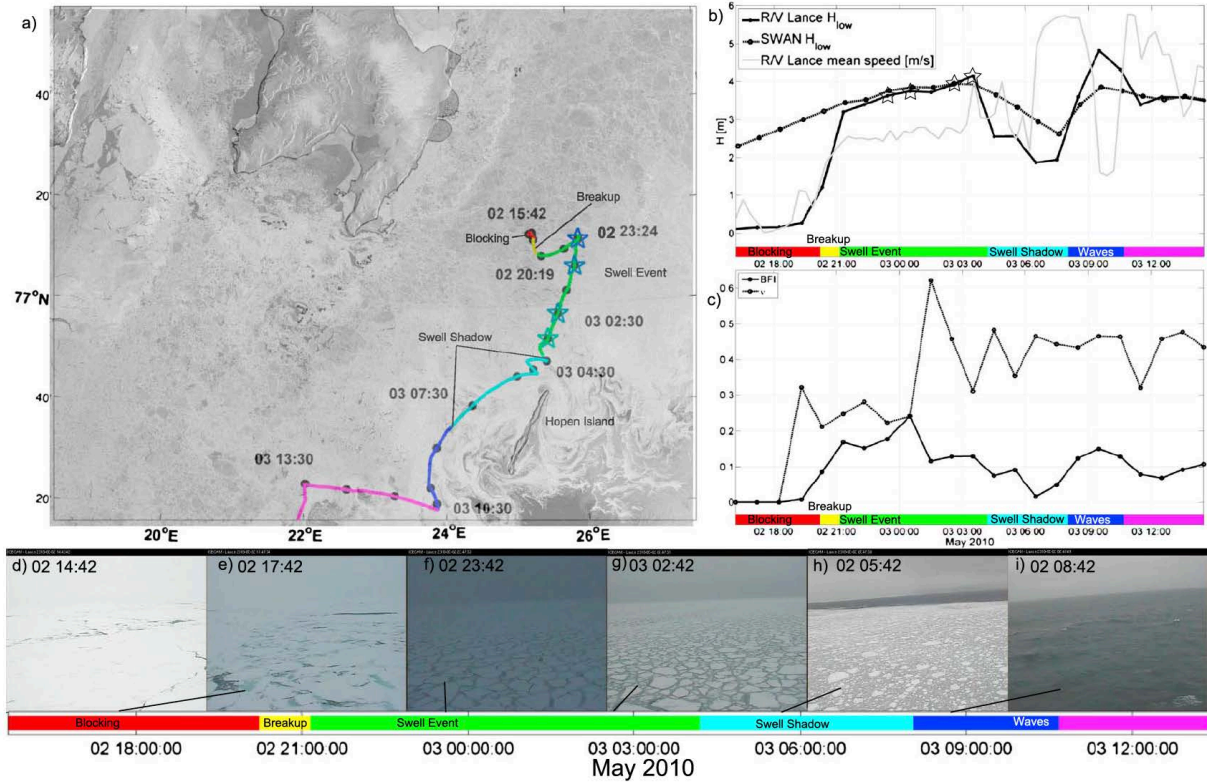


Figure 5. (from Collins et al., 2015) (a) Map of southern Svalbard in the top left and Hopen Island in the bottom right. The ship track is in colors corresponding to different phases of wave interaction (red: wave blocking by ice, yellow: arrival of waves and breakup of the ice, green: swell event at full energy allowing higher frequencies with time, cyan: the swell shadow of Hopen Island, blue and purple: after the swell shadow). The background is superimposed with an advanced synthetic aperture radar image provided by Benjamin Holt at the JPL. (b) Time series as measured by R/V Lance (black solid line) and predicted by SWAN (black dashed line) and the ship velocity (grey solid line). (c) BFI (black solid line) and nondimensional spectral width v (black dashed line). (d–i) Selected photographs from the ship show local sea ice state.

Fig. 6 illustrates a laboratory experiment (Bennetts et al., 2015) intended to study scattering and dissipation of wave energy by idealised ice floes. Left panel explains the experimental setup, and right panel displays results for two different steepnesses of incident waves. For the low steepness of $ka=0.04$, the observed decay is largely due to scattering, the waveform is clearly maintained. Significant distortion of the waveforms occurs for steeper waves of $ka=0.015$, due to overwash of the floe which causes permanent loss of energy by the wave train. Note that the overwash effect is most essential for the dissipation, but cannot be depicted theoretically and has to be parameterised through observations. In the paper, the transmission coefficient is shown to decrease as incident wave steepness increases, and to be at its minimum for an incident wavelength equal to the floe length.

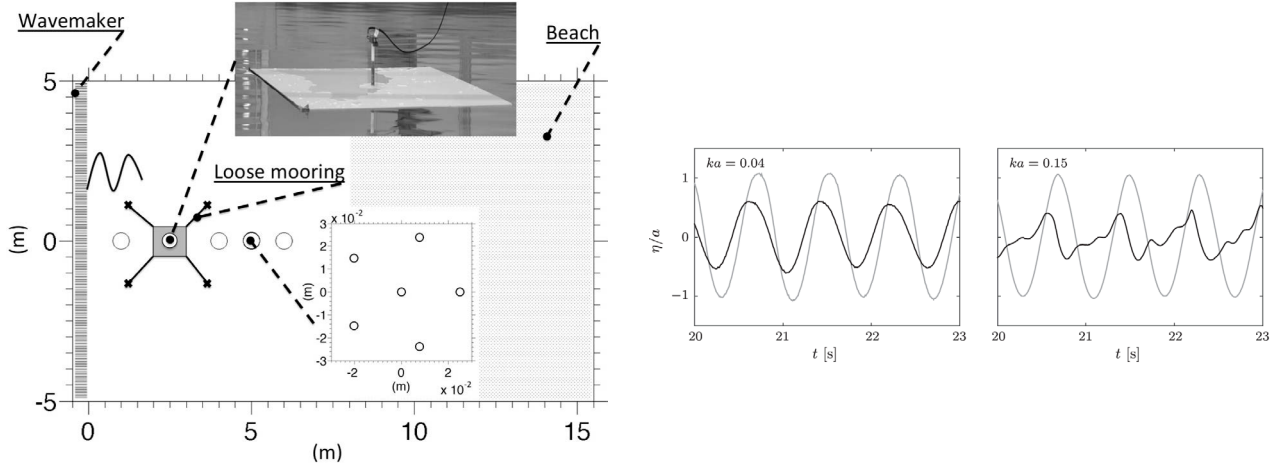


Figure 6. (from Bennetts et al., 2015) (left) Schematic of the wave basin and experimental set-up. Circles denote locations of the wave gauges. Top inset is a photo of the model floe, which shows the gauge used to measure overwash. Bottom inset shows the hexagonal wave array in the lee of the floe. (right) Surface elevation in the lee of a 5 mm thick polypropylene floe (thick black curves) and incident wave (grey), normalised with respect to target incident amplitude. Nondimensional incident wavelength $L(\text{wave})/L(\text{floe})=1:00$, and steepness $ka=0.04$ (left-hand panel) and 0.15 (right).

Other results relate to the wave-modelling part of the project. Zieger et al. (2015) describes a new release of WAVEWATCH-III model, with observation-based physics. The new source terms include wind input, whitecapping dissipation, swell dissipation and negative input (wave dissipation due to adverse winds).

The least well performing metrics of wave models is usually directional spectra of the waves. This is due to two different reasons: details of directional behavior of the source functions which produce such waves are unknown; and relative performance of methods, which are typically used to measure directional spectra, is not well understood and quantified. Donelan et al. (2015) compares three directional methods, Maximum Likelihood Method (MLM, Capon (1969)), Maximum Entropy Method (MEM, Lygre and Krogstad (1986)) and Wavelet Directional Method (WDM, Donelan et al. (1996)), on the basis of field data and outputs of fully nonlinear three-dimensional wave model (Chalikov and Babanin, 2013) for which the Fourier directional spectrum is known explicitly.

The wave models usually concentrate on performance with respect to wind-forced waves, but in 85% of oceanic wave fields swells are also present. In modern models, attenuation of swell is accounted for through its dispersion (Ardhuin et al., 2009, Young et al., 2013), and dissipation as a result of interaction with the turbulence in the water (Babanin, 2006) and in the air (Ardhuin et al., 2009). Within current project, Babanin and Waseda (2015) investigated diffraction of short-crested waves by means of laboratory experiments in directional wave tank and found nonlinear behavior of such diffraction, when rate of the lateral spread of wave crests into undisturbed waters depends on wave steepness. The paper also discusses possibility of coherent one-dimensional structures on the two-dimensional wave surfaces which implies one-dimensional behaviours, such as modulational instability in two-dimensional environments.

IMPACT/APPLICATIONS

The existing Swinburne satellite database is extended. For the altimeter, this includes the new data of the continuing CRYOSAT mission, as well as the data from China's altimeter HY2 and Indian-French altimeter SARAL. Apart from the altimeter, the new database now incorporates all the ocean wind/wave satellite data available: SSM/I radiometers (wind speed), scatterometers (wind speed and direction) and Synthetic Aperture Radar (SAR, full directional wave spectrum) (Young et al., 2015). Such database can be employed across the entire range of long-term global wind-wave applications.

TRANSITIONS

The new version of WAVEWATCH-III, with the WBL module as wind input, has been registered as ST7 and added to the NCEP/NOAA repository. It can now be shared for additional validation and testing of the source terms, with other WAVEWATCH-III developers. CRYOSAT data was utilised for the validation tests and for the Arctic wave climatogoly. Together with the ice trends based on ENVISAT dataset, these were used to contribute to the community paper (Thomson et al., 2015).

RELATED PROJECTS

This project is part of ONR Sea State DRI whose projects are all related. Particularly closely related are

Rogers, W.E, Posey, P.G. "Wave-ice interaction in the Marginal Ice Zone: toward a wave-ocean-ice coupled modeling system"

Gemmrich, J., Lehner, S. "Wave processes in Arctic Seas, observed from *TerraSAR-X*"

Shen, H. "An Integrative Wave model for the Marginal Ice Zone based on a Rheological Parameterization"

Squire, V., Williams, T., Holt, B. "An Arctic Ice/Ocean Coupled Model with Wave Interactions"

Other Related Projects

Babanin, A.V., Walsh, K., Young, I.R., Sandery, P.A., Hemer, M.A., Qiao, F., Ginis, I. "Coupling tropical cyclone and climate physics with ocean waves", Australian Research Council (ARC) Discovery grant. Coupled wind/wave/ocean physics in large-scale air-sea applications

Monty, J., Babanin, A.V., Meylan, M., Bennetts, L., Toffoli, A., Marusic, I., Klewicki, J., Hutchins, N., Suslov, S., Walker, D., Chung, D., "A Thermally Stratified Sea-Ice-Wave Interaction Facility", ARC Linkage Infrastructure and Facility grant

Young, I.R., Babanin, A.V., Hemer, M.A., Aster, R.C. "Global trends in oceanic wind speed and wave height", ARC Discovery grant. Creation of the global satellite wind and wave database and investigation global and regional trends

REFERENCES

References to the 2015 publications by PIs are in Publications below

Ardhuin, F., E. Rogers, A.V. Babanin, J.-F. Filipot, R. Magne, A. Roland, A. Van der Westhuysen, P. Queffelecoulou, J.-M. Lefevre, L. Aouf, and F. Collard, 2010: Semiempirical Dissipation

- Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation. *J. Phys. Oceanogr.*, 40(9), 1917–1941, doi:10.1175/2010JPO4324.1
- Ardhuin, F., B. Chapron, and F. Collard, 2009: Observation of swell dissipation across oceans. *Geophys. Res. Lett.*, 36, doi:10.1029/2008GL037030
- Babanin, A.V., 2006: On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophys. Res. Lett.*, 33, doi:10.1029/2006GL027308
- Babanin, A.V., and V.K. Makin, 2008: Effects of wind trend and gustiness on the sea drag: Lake George study. *J. Geophys. Res.*, 113, C02015, doi:10.1029/2007JC004233, 18p
- Babanin, A.V., K.N. Tsagareli, I.R. Young, and D.J. Walker, 2010: Numerical investigation of spectral evolution of wind waves. Part 2. Dissipation function and evolution tests. *J. Phys. Oceanogr.*, 40, 667–683
- Babanin, A.V., 2011: *Breaking and Dissipation of Ocean Surface Waves*. Cambridge University Press, 480p
- Babanin, A.V., S. Zieger, and A. Ribal, 2014: Satellite observations of waves in the Arctic Ocean. *Proc. 22nd IAHR Int. Symp. on Ice*, Singapore, August 11–15, 12p
- Capon, J., 1969: High-resolution frequency-wavenumber spectrum analysis. *Proc. IEEE*, 57, 1408–1418
- Chalikov, D. and S. Rainchik, 2011: Coupled numerical modelling of wind and waves and the theory of the wave boundary layer. *Boundary-Layer Meteorol.*, 138 (1), 1–41
- Chalikov, D., and A.V. Babanin, 2013: Three-dimensional periodic fully-nonlinear potential waves. *Proc. ASME 2013 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2013*, June 9–14, 2013, Nantes, France, 8p
- Donelan, M. A., W. M. Drennan, and A. K. Magnusson, 1996: Non-stationary analysis of the directional properties of propagating waves. *J. Phys. Oceanogr.*, 26, 1901–1914
- Lygre, A., and H. E. Krogstad, 1986: Maximum entropy estimation of the directional distribution in ocean wave spectra. *J. Phys. Oceanogr.*, 16, 2052–2060
- Rogers, W.E., A.V. Babanin, and D.W. Wang, 2012: Observation-consistent input and whitecapping-dissipation in a model for wind-generated surface waves: Description and simple calculations. *J. Atmos. Oceanic Tech.*, 29(9), 1329–1346
- Tsagareli, K.N., A.V. Babanin, D.J. Walker, and I.R. Young, 2010: Numerical investigation of spectral evolution of wind waves. Part 1. Wind input source function. *J. Phys. Oceanogr.*, 40, 656–666
- Tran, N., F. Girard-Ardhuin, R. Ezraty, H. Feng, and P. Féménias, 2009: Defining a sea ice flag for envisat altimetry mission. *IEEE Geosci. Rem. Sens. Lett.*, 6 (1), 77–81
- Laxon, S., 1990: Seasonal and inter-annual variations in antarctic sea ice extent as mapped by radar altimetry. *Geophys. Res. Lett.*, 17 (10), 1553–1556, doi:10.1029/GL017i010p01553.
- Rinne, E. and H. Skourup, 2012: Sea ice detection using ENVISAT radar altimeter 2. *AGU Fall Meeting*, San Francisco, CA, December 3–7, eposter
- Ting, C.-H., A.V. Babanin, D. Chalikov, and T.-W. Hsu, 2012: Dependence of drag coefficient on the directional spreading of ocean waves. *J. Geophys. Res.*, 117, doi:10.1029/2012JC007920, 7p
- Toffoli, A., L. Loffredo, P. Le Roy, J.M. Lefevre, and A.V. Babanin, 2012: On the dependence of sea drag in finite water depth. *J. Geophys. Res.*, 117, doi:10.1029/2011JC007857, 10p

Young, I.R., S. Zieger, and A.V. Babanin, 2011: Global trends in wind speed and wave height. *Science*, 332, 451–455

Young, I.R., J. Vinoth, S. Zieger, and A.V. Babanin, 2012: Investigation of trends in extreme value wave height and wind speed. *J. Geophys. Res.*, 117, doi:10.1029/2011JC007753, 13p

Young, I.R., A.V. Babanin, and S. Zieger, 2013: The decay rate of ocean swell observed by altimeter. *J. Phys. Oceanogr.*, 43, 2322–2333

PUBLICATIONS

Journals and thesis

Bennetts, L.G., A. Alberello, M.H. Meylan, C. Cavaliere, A.V. Babanin, and A. Toffoli, 2015: An idealised experimental model of ocean surface wave transmission by an ice floe. *Ocean Modelling*, 8p, <http://dx.doi.org/10.1016/j.ocemod.2015.03.001> [published, refereed]

Collins, C.O., W.E. Rogers, A. Marchenko, and A.V. Babanin, 2015: In situ measurement of an energetic wave event in the Arctic marginal ice zone. *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL063063, 8p [published, refereed]

Donelan, M., A.V. Babanin, E. Sanina, and D. Chalikov, 2015: A comparison of methods for estimating directional spectral of ocean waves. *J. Geophys. Res.*, 120, 5040–5053 [published, refereed]

Sanina, E.: Three Dimensional Properties of Fully Nonlinear Surface Waves. *PhD Thesis*, Swinburne University of Technology [published, refereed]

Thomson J. et al. (ONR Arctic Sea DRI Team), 2015: Emerging trends in the Sea State of the Beaufort and Chukchi Seas. *Ocean Modelling*, submitted

Zieger, S., A.V. Babanin, W.E. Rogers, and I.R. Young, 2015: Observations-based input and dissipation terms for WAVEWATCH III. *Ocean Modelling*, in press [published, refereed]

Other

Babanin, A.V., and T. Waseda, 2015: Diffraction and instability of short-crested limited-length one-dimensional coherent wave trains. *Proc. ASME 2015 34th Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2015, May 31 - June 5, 2015, St John's, NL, Canada*, 8p [published, refereed]

Young, I.R., S. Zieger, and A.V. Babanin, 2015: Development and application of a global satellite database of wind and wave conditions. *Proc. ASME 2015 34th Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE2015, May 31 - June 5, 2015, St John's, NL, Canada*, 9p [published, refereed]